06 Oct 1971

Experiments in Magneto-Fluid-Mechanic Natural and Forced Heat Transfer from Horizontal Hot-Film Probes

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EXPERIMENTS IN MAGNETO-FLUID-MECHANIC NATURAL AND FORCED HEAT TRANSFER FROM HORIZONTAL HOT-FILM PROBES

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ABSTRACT

Experiments investigating magneto-fluid-mechanic effects on the heat transfer of quartz-coated hot-film probes are described. A standard heat transfer-velocity calibration curve is obtained by traversing a probe, whose axis is aligned horizontally, in the presence of a magnetic field parallel to the probe's axis. The working medium is mercury. Results indicate a significant reduction of the probe's heat transfer in both the free and forced convection regimes.

INTRODUCTION

This paper presents results of an experimental investigation of the effect of a transverse magnetic field upon the heat transfer from a cylindrical quartz-coated platinum hot-film probe (0.015 cm diameter) in a cross flow of mercury. The length to the diameter ratio of the probe is 13.4:1. In this experiment the Reynolds number varied from 0 to 130 and the Hartmann number varied from 0 to about 5. Four distinct regions of heat transfer were identified, each associated with a specific flow configuration about the probe.

EXPERIMENTAL APPARATUS

Probe calibrations in the presence of a magnetic field can be accomplished by traversing a probe at various velocities through mercury and recording its bridge voltage output (Figure 1). The system must be designed to be free of vibrations over a range of constant velocities.

In this experiment a probe holder was mounted on a stainless steel plate which was connected at its top to a support plate (Figure 2). A linear bearing-guide rod system was aligned parallel to a turn screw passing through the support plate. The turn screw was driven via a Pic belt and pulleys by a variable speed motor. The iron structure housing the traversing mechanism was mounted on the top of the Magneto-Fluid-Mechanic Laboratory's d.c. electromagnet. A rectangular stainless steel tank (15.2 cm x 5.7 cm x 73.7 cm) was filled with triple distilled mercury and placed between the polefaces of the electromagnet. A maximum field of 15,000 Gauss could be obtained between the poleface gap (7.7 cm wide).

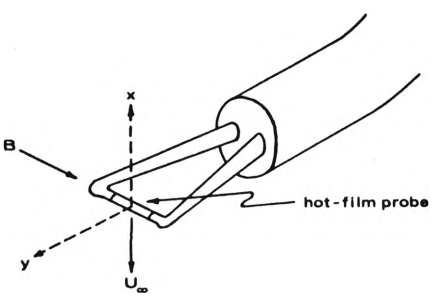

Figure 1 - Geometry of the Problem

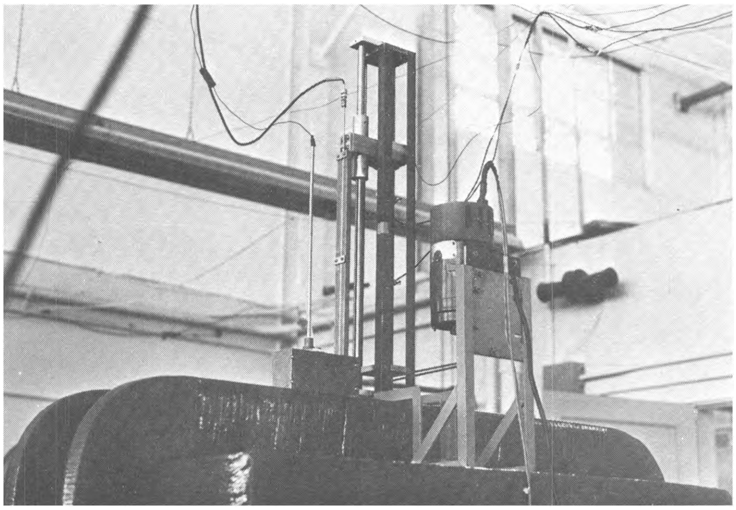

Figure 2 - Experimental Apparatus

MEASUREMENTS

The essential parameters to be measured were the probe velocity, the environmental temperature, the average bridge voltage of the anemometry system and the magnetic field strength.

The test region was located from 3 cm after the beginning to 3 cm before the end of the poleface region. Two microswitches were positioned on the traversing mechanism structure. Thus, as the probe traveled through the test region, each microswitch was triggered at the appropriate time, sending start and stop commands to the recording equipment.

The velocity was computed from the distance between the microswitches (25.4 cm) and the time recorded on a Universal time counter. A linear potentiometer was mounted on the top of the structure to check for constant velocity. A string was wound around its axis and connected to the probe support plate. The output of the potentiometer, connected in series with a 15 volt dry cell, was displayed on a Tektronik storage oscilloscope. A linear trace indicated a constant velocity.

The environmental temperature of the mercury was measured from an iron-constantan thermocouple placed in the center of the test region. It was monitored on a VIDAR integrating digital voltmeter.

An integrated bridge voltage from the output of a Thermo-Systems Inc. 1050 constant temperature anemometer was obtained by using the microswitches. From this integrated bridge voltage and the time of traverse, an average bridge voltage was calculated. The anemometer output was also connected to a Thermo-Systems Inc. RMS voltmeter to check if vibrations in the system produced velocity fluctuations of turbulence level (> 0.5% RMS).

The magnetic field strength was measured from the voltage drop of a shunt in series with the coil of the electromagnet (calibrated with a Scalamp fluxmeter).

To insure reproducibility of the data, each experimental run at a velocity was repeated three times.

RESULTS

The heat transfer of the probe was correlated with the velocity and magnetic field strength through the nondimensional Nusselt, Reynolds, and Hartmann numbers.

The expression for the Nusselt number was found by equating the power supplied to the probe with the heat flux from the probe to the mercury. All Nusselt numbers were referred to the same temperature.[1] The characteristic length of the Reynolds and Hartmann numbers was chosen to be the diameter of the probe. The respective Reynolds and Hartmann numbers for each Nusselt number were calculated.

The results of the experiment are shown in Figures 3 and 4 and in a qualitative manner in Figure 5. Four distinct regions of flow are identified.

A. The region of free convection. Here the application of a magnetic field suppresses the free convection and eventually limits the heat transfer mechanism to thermal conduction.

B. The region of forced convection for very low Reynolds numbers. In the absence of a magnetic field it is known that below a characteristic Reynolds number, the Nusselt number remains the same as the one observed for natural convection. When a magnetic field is applied, the Reynolds number up to which free convection prevails is lowered, becoming smaller for higher magnetic fields (See dotted line in Figure 4).

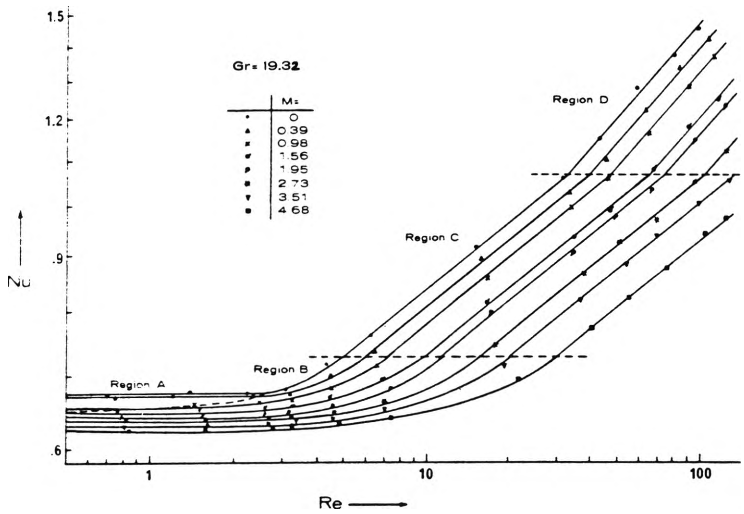

Figure 3 - Nondimensional Calibration Curves

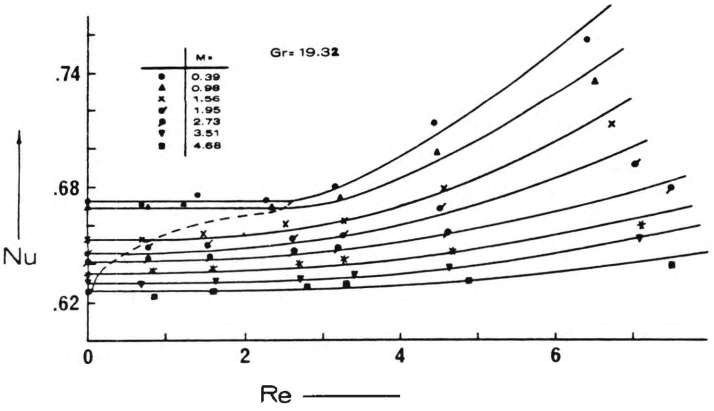

Figure 4 - Nondimensional Calibration Curves for Low Reynolds Numbers

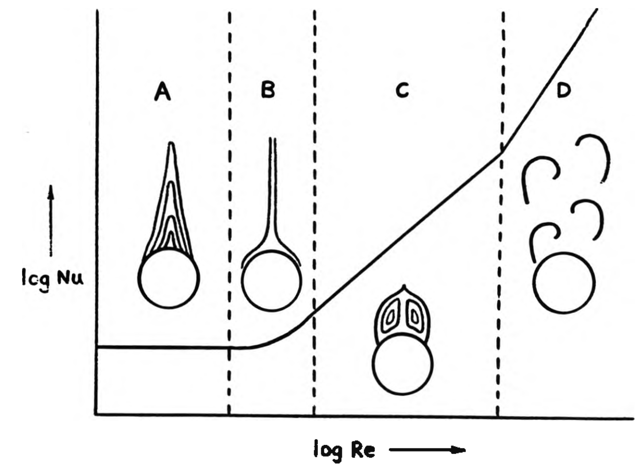

Figure 5 - Qualitative Calibration with Flow Configurations

C. The region of the stagnant twin vortex pool (Föppl vortex formation). In this case the magnetic field acted only to delay the onset of the vortex pool. However, after this pool was formed, the Nusselt versus Reynolds number dependence adopted a power law. In fact, it was found for different magnetic fields that this power remained unchanged. For the same Reynolds number, increasing the magnetic field decreases the value of the Nusselt number as one would have expected because of the retardation of the flow by the magnetic field.

D. The region of the von Karman vortices. In the absence of the magnetic field the von Karman vortices are shed at a Reynolds number approximately larger than 40. It was found that these vortices are initiated at a higher Reynolds number in the presence of a magnetic field. In this region it was also observed that the Reynolds and Nusselt numbers were correlated with a power law, the power now being higher than in the previous region. This power also remained unchanged for different magnetic fields.

Typical power law relations found in region C ranged between 0.12 and 0.36 and in region D between 0.25 and 0.50. These variations (also reported by other investigators calibrating in mercury) have been attributed to interface effects between the quartz insulation and mercury which lower the probe's heat transfer.[2-5]

Malcolm[7] has also conducted experiments of a similar geometry in mercury. His conclusions that electromagnetic effects do not alter the heat transfer in the forced convection regime are at variance with the present findings.

DISCUSSION OF RESULTS

All of the above experimental results have been analyzed. Quantitative relations have been developed for each region from an approximate theory.[6] A summary follows.

For the magnetic case one reasons that region A begins at a lower heat transfer value due to magnetic field damping of free convection. This diminished free convection permits initial forced convection (region B) to predominate at a lower Reynolds number. Region B terminates when a specific flow configuration, the Föppl vortex pool, starts to grow behind the probe. Assuming that each flow geometry corresponds to a unique heat transfer value, one concludes that region C begins along a constant Nusselt number line (which is substantiated experimentally). In region C the magnetic field acts only to suppress the probe's flow configuration. Therefore, the same power law holds as in the non-magnetic case. Region D's onset is due to the detachment of the vortices from behind the probe. This occurs along a constant Nusselt number line since each heat transfer value corresponds to a specific shedding geometry. Again, the power law in region D remains the same as in the non-magnetic case. Electromagnetic alteration of the von Karman vortex street wake for this geometry has been observed by Papailiou.[8] The power law exponent of region D is greater than that of region C because a more effective mechanism of heat transfer from the probe is present.

ACKNOWLEDMENTS

The authors acknowledge the assistance of the Aerospace Sciences Laboratory personnel in the construction of the apparatus, especially Messers. Ron Metsger and Russ Carlson. The financial support of the National Science Foundation under Grant No. GK-23694 is gratefully recognized.

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DISCUSSION

V. W. GOLDSCHMIDT (Purdue University): In your experiment the probe was moving into a stagnant fluid. However, the heat transfer coefficient around a cylinder can depend on upstream turbulence effects. Hence what you are suggesting may not be the same as that which might result when the probe is standing still and the fluid is moving towards it, even though the relative velocity may be the same in both cases. In one there is no upstream turbulence, in the other there is. In addition, in your case the flow is homogeneous with no velocity gradients nor shear. Any orderly wake structure downstream of a cylinder has a certain dependence on Reynolds number and may become distorted in the presence of a velocity gradient and non-uniform distribution along the axis of the cylinder. These probably exist when the probe is placed in a turbulent flow. What precautions should we take when trying to extend your results to actual set-ups where we are trying to measure turbulence intensities?

DUNN: To extend this technique, for instance, to turbulent shear magneto-fluid-mechanical channel or pipe flows requires velocity profiles for each magnetic field and flow Reynolds number. This is because the Hartmann flattening of the velocity profile must be accounted for. Since results in this experiment are only in the laminar regime (probe Reynolds number from 0 to about 130), it would be speculation to say what would happen in the turbulent regime. The only reported observation of magnetic field effects on probe heat transfer for the turbulent regime is that of Dr. Gardner (Washington University). He, in fact, observed an increase in the probe heat transfer with magnetic field strength.